Modeling of laser-plasma interaction for EUV sources toward high power and efficiency

Akira Sasaki

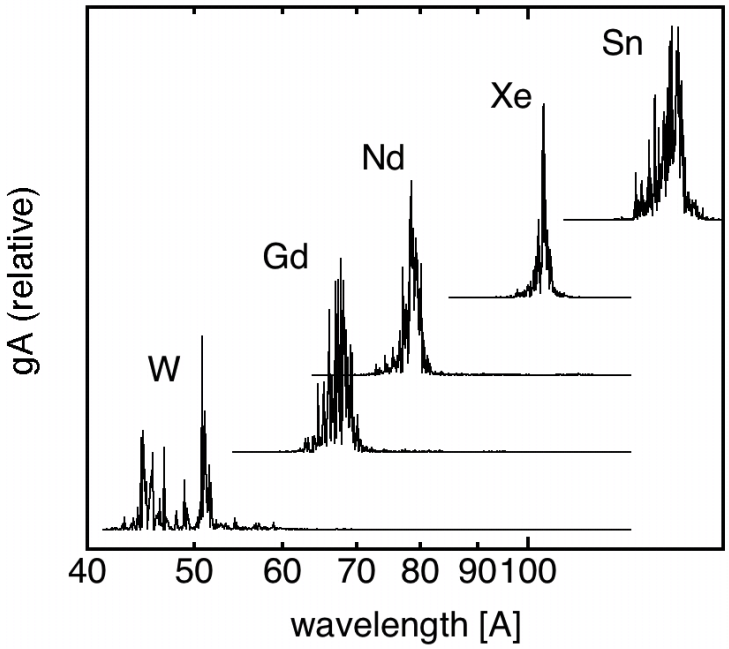
Japan Atomic Energy Agency

Introduction

- Present status of development of EUV source
- Subjects of the basic research
  - Modeling atomic process
  - Modeling hydrodynamics of the plasma
- Summary

Present status of development of EUV source

- Study of short wavelength source for future lithography.
  - 4d-4f transition can be scalable to 6.5nm.
  - Higher temperature is required.

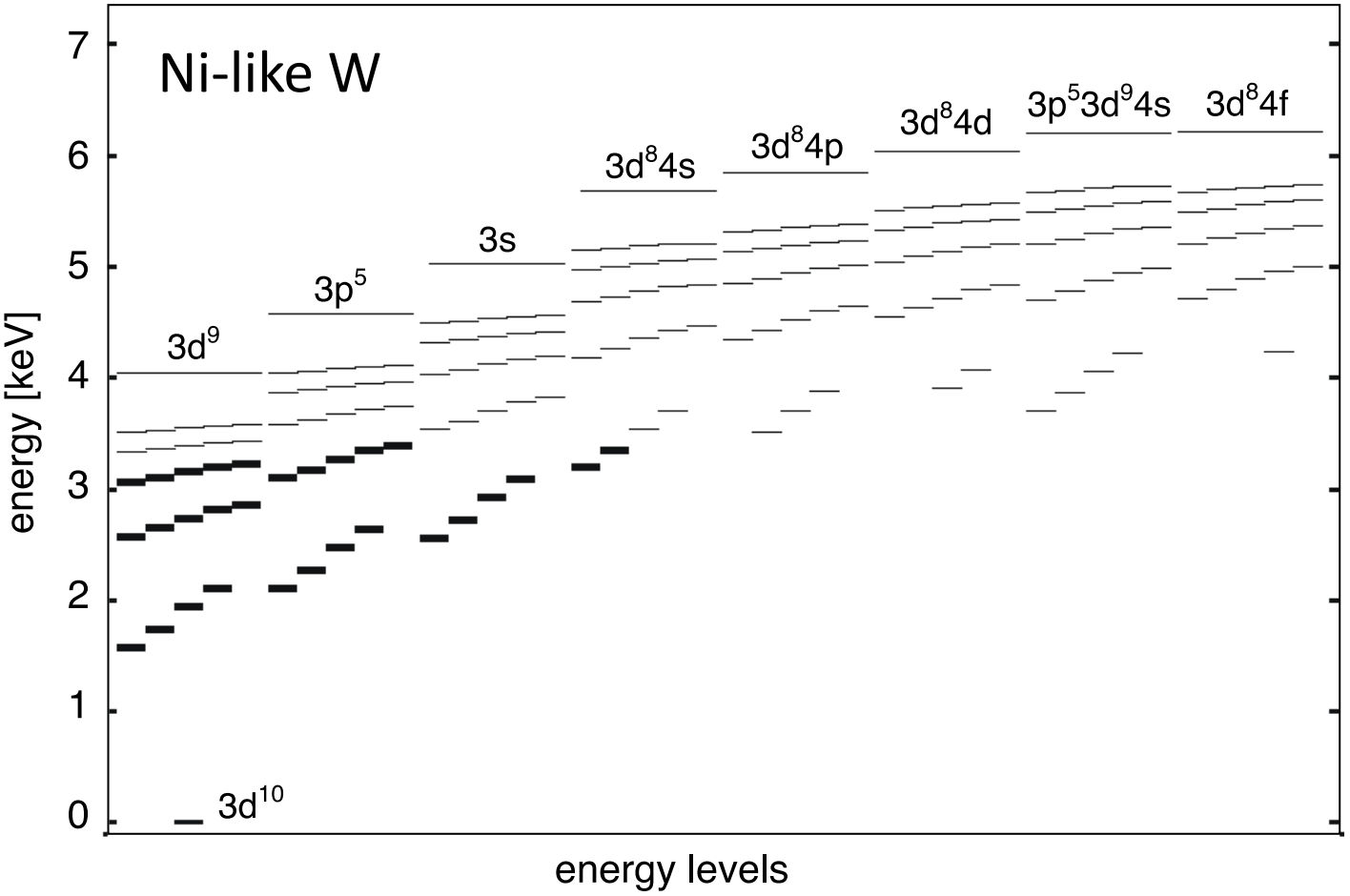


- Improvement of efficiency of 13.5nm source
  - Power > 1kW will be required.

Accurate modeling of atomic process and radiation hydrodynamics is required for optimization.

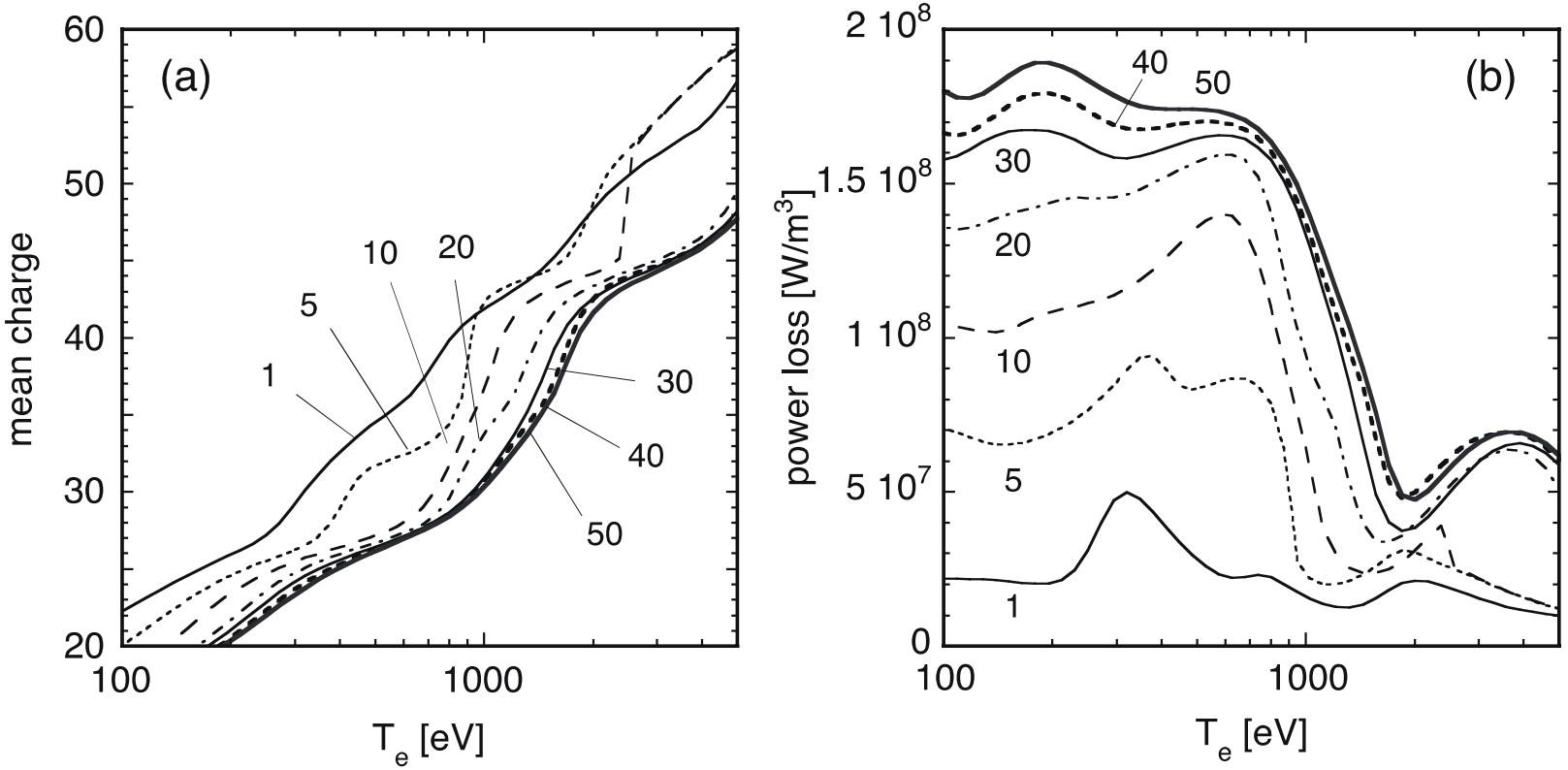
Atomic structure of Ni-like W

- Validation of atomic model of W is carried out in the study of fusion plasmas, for the plasma facing material of ITER and future reactors.

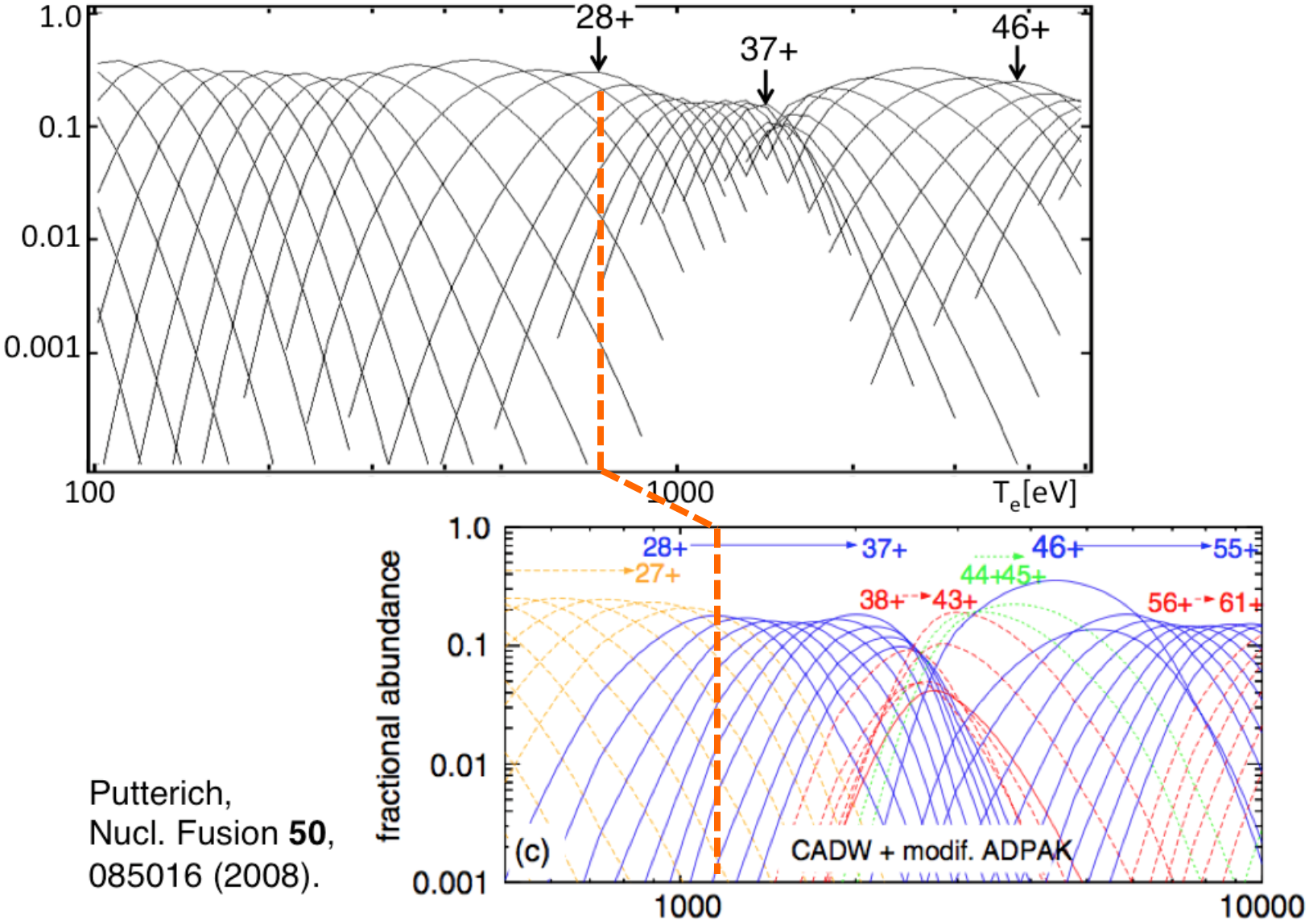


Modeling atomic processes

- Mean charge and radiative power loss are useful for estimating pumping power to obtain EUV emission.
- Convergence with respect to size of the model and satellite contribution is investigated.



Significant difference of calculated ion abundance of W between existing codes.

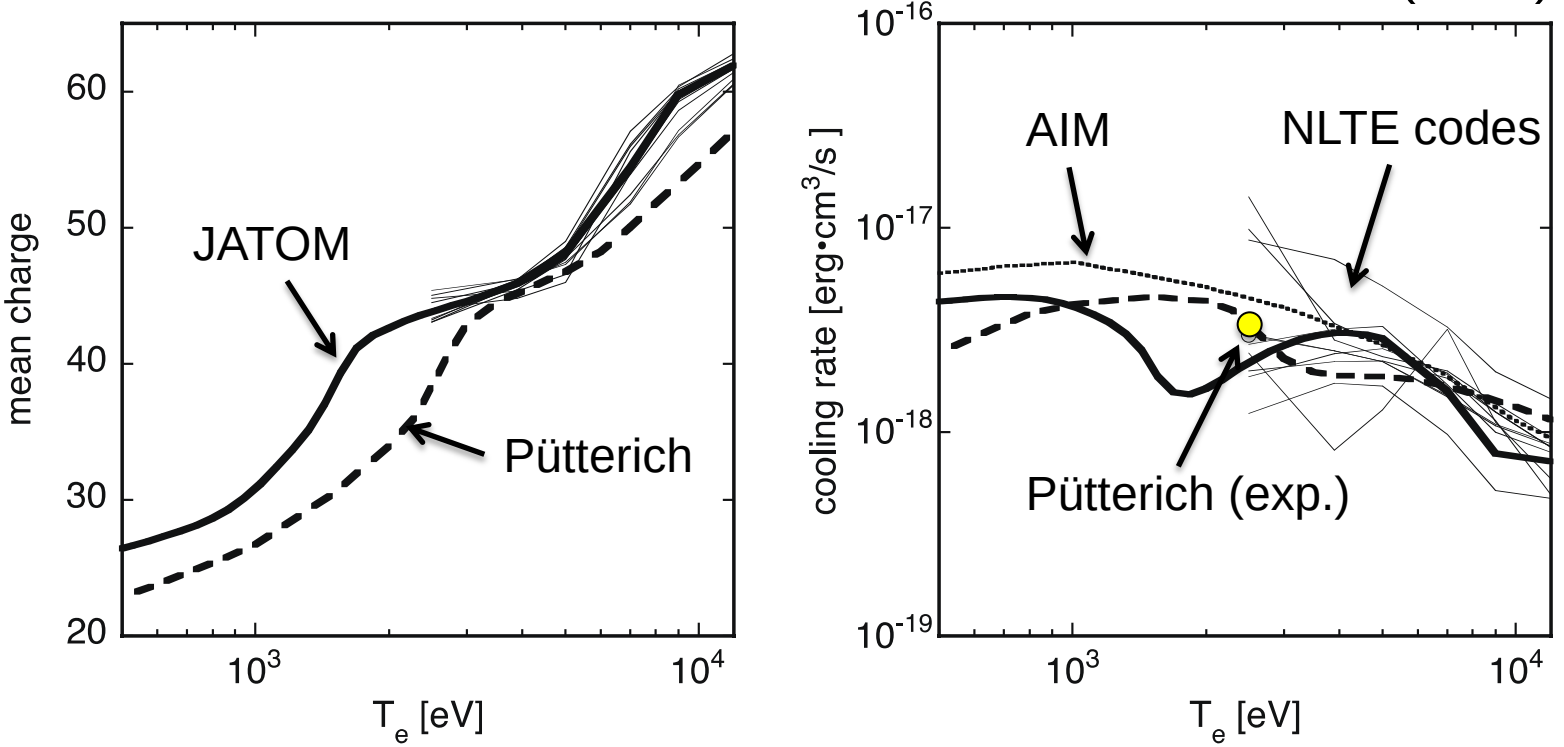


Putterich,
Nucl. Fusion **50**,
085016 (2008).

Validation of cooling rate

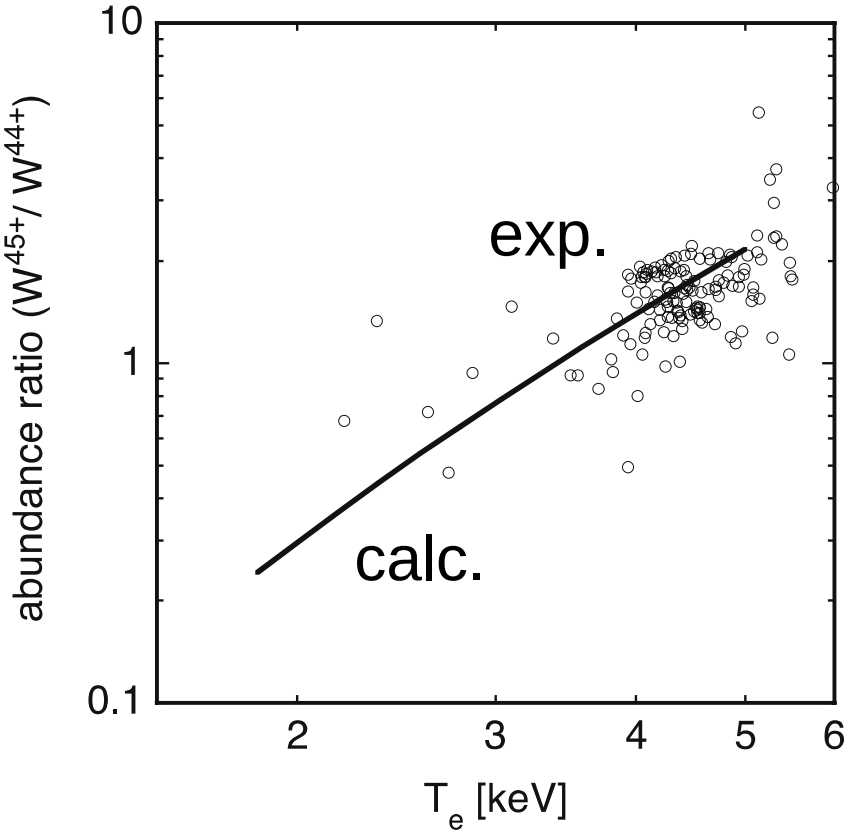
- Calculations reproduces cooling rate at 2.5keV. However, experimental data for validation is limited.
- Calculations presented at code comparison workshop agree each other.

Pütterich, et al. Nucl Fusion, 50, 025012 (2010)



Benchmarking of the collisional radiative model

- Ratio of W^{44+} and W^{45+} are measured from the intensity ratio of line emissions near 6nm.
- Calculation agrees well with experiment.



$n_e=10^{14}/cm^3$

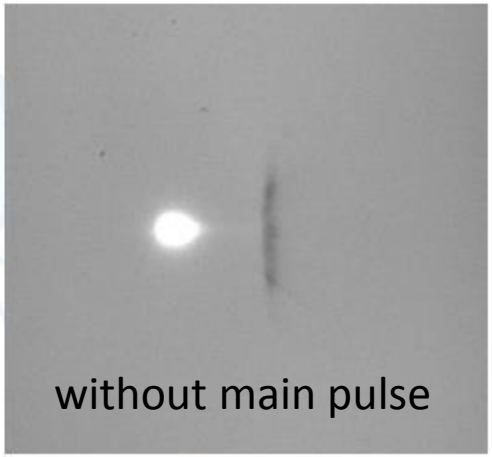
T. Nakano, J. Nucl. Mater. 415, S327 (2011)

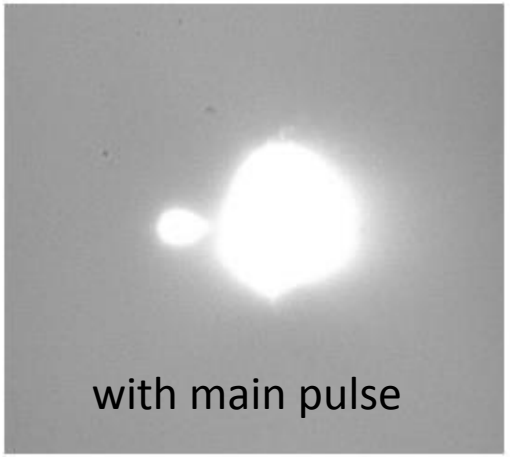
Present status of modeling atomic processes

- Calculation of mean charge and radiative loss has been improved through theoretical and experimental validation.
- Development of coupled atomic processes and radiation hydrodynamics simulation remains to be a critical issue in the modeling; multidimensional simulation requires reduction of atomic structure, and spectral resolution.

Modeling hydrodynamics of the plasma

- High efficiency (>3%) is obtained by optimizing double pulse irradiation; pumping Sn mist produced by irradiating small droplet by ps prepulse.

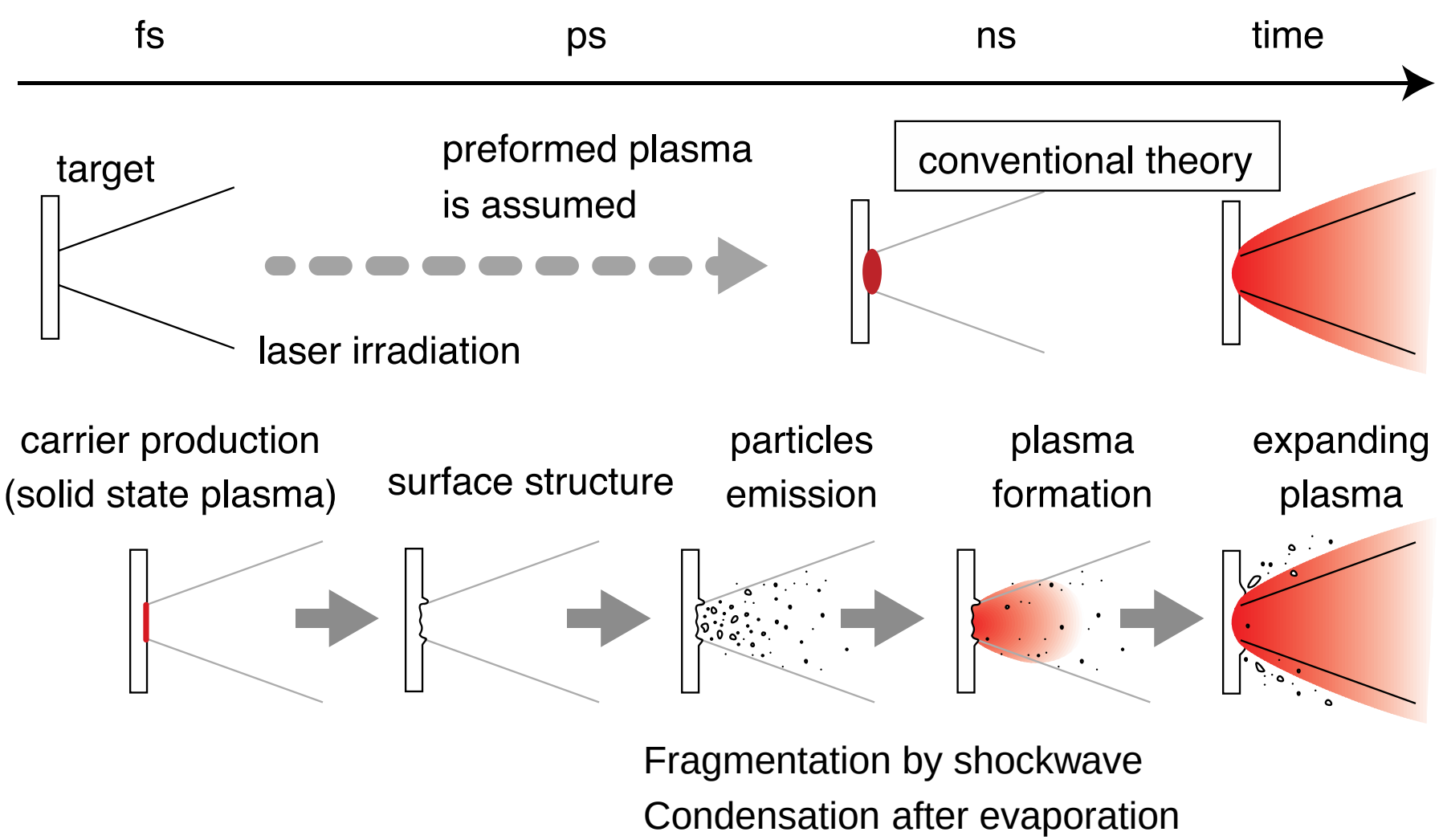




Endo EUV source workshop 2012 (Gigaphoton data)

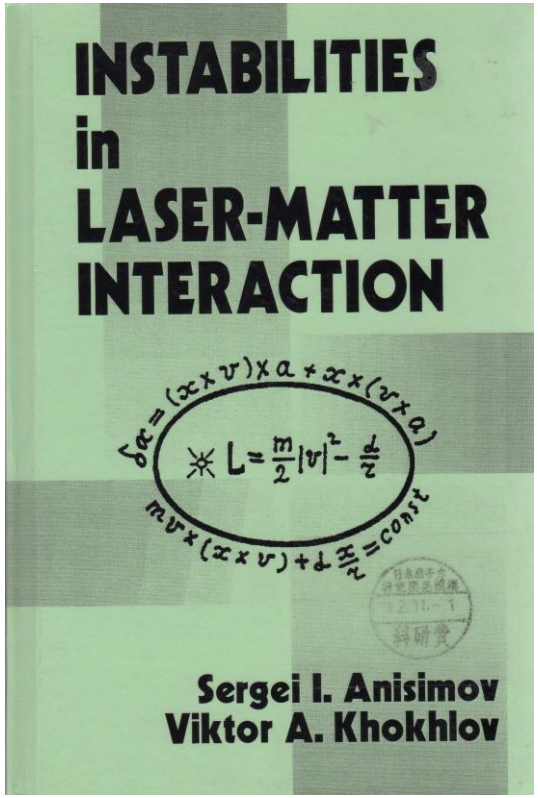
- Formation of Sn mist and interaction of laser with mist cannot be calculated using conventional model.

Scenario of excitation of LPP



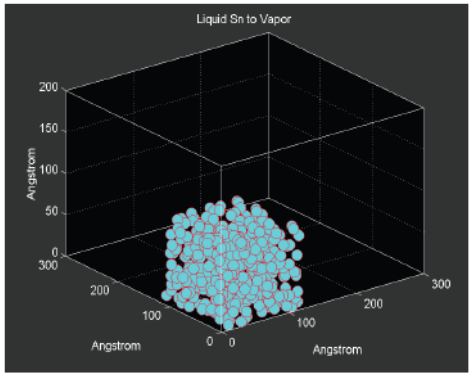
Simulation methods for initial plasma formation

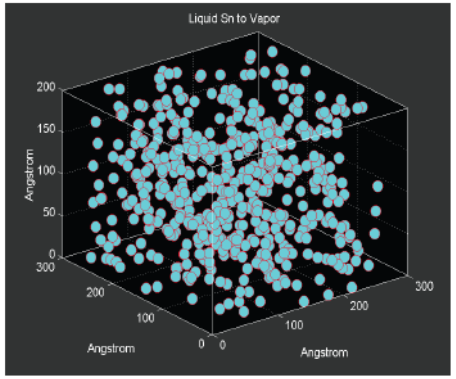
- Hydrodynamics simulation is required to perform calculation from initial plasma formation by prepulse, heating by main pulse, to EUV emission.
- Initial plasma formation is unstable; new hydrodynamics model which takes solid/liquid to gas/plasma phase transition including effect of instabilities into account should be developed.



Simulation methods for initial plasma formation

- Molecular dynamics simulation qualitatively shows the expansion of droplet, but cannot be applied to real-scale calculation.



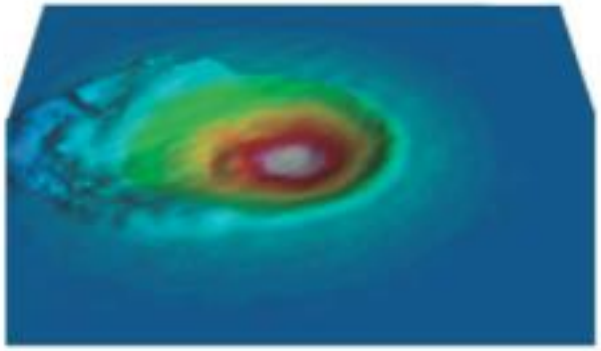


Masnavi, 2009 EUVL workshop

MD

Particle method

Endo, EUVL workshop 2012



Surface tracking

Yamashita, Q .J. Jpn. Weld Soc. 2011

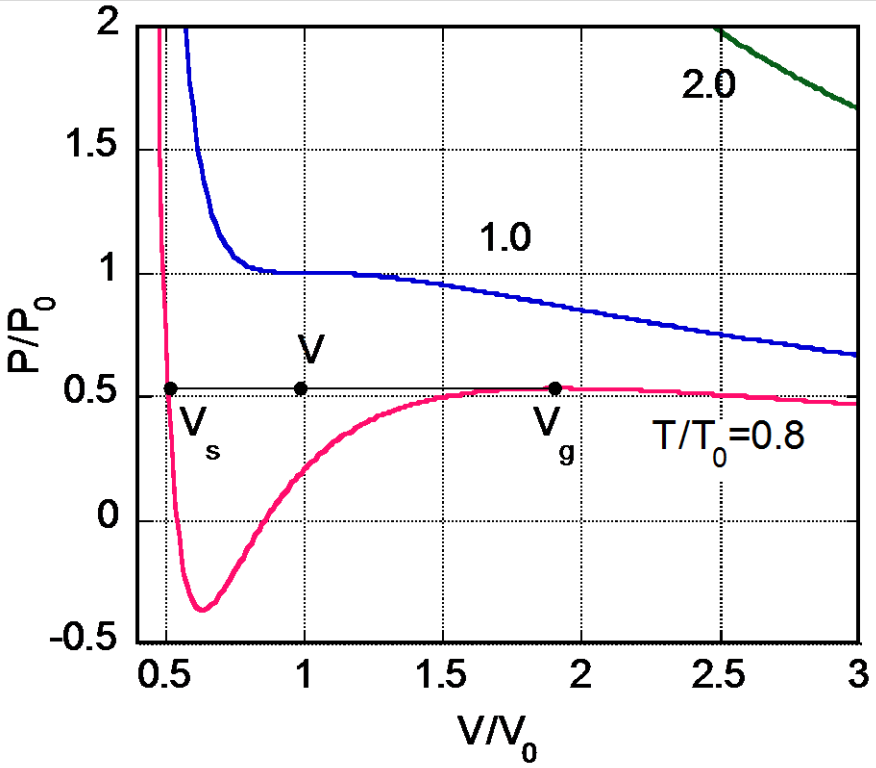
Alternative hydro simulation methods

- Particle methods are useful but limited to incompressible fluid (MPS) because it is difficult to conserve mass and energy.
- Surface tracking method is useful for cutting and welding simulations but difficult to calculate boiling and cluster formation problems.

Modeling hydrodynamics

- 2-d hydrodynamics code based on Lagrange mesh.
  (equation of motion, energy, and EOS)
- Re-meshing to calculate large motion of the fluid.

Van-der-Waars equation of state

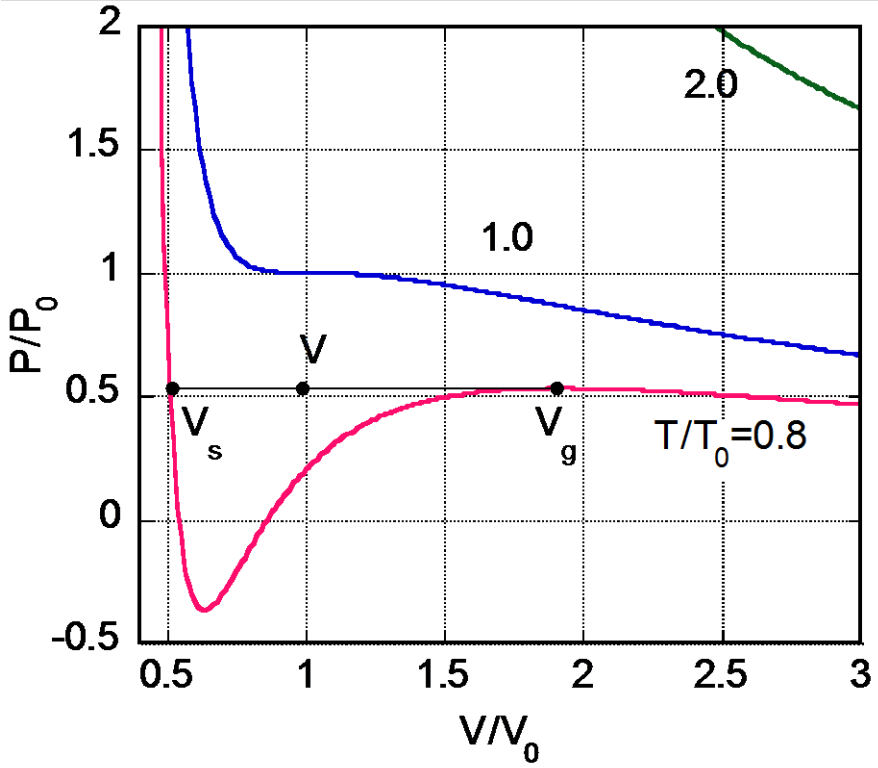


- Phase transition is taken into account; to maintain thermodynamic consistency and avoid numerical instability.
- Includes stochastic structure formation.

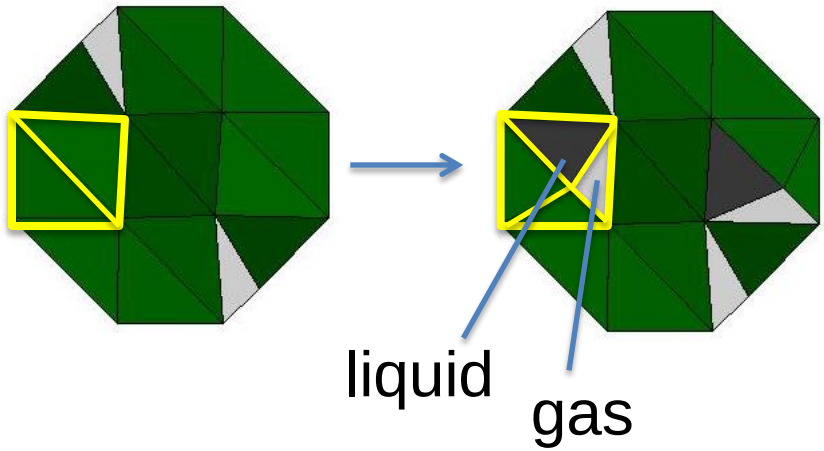
Modeling phase transition

- When a density of a cell becomes those of 2 phase region, the cell is split to solid (V_s) and gas (V_g) cell.
- 2 triangular cells are divided into 4 triangular cells.

Van-der-Waars equation of state

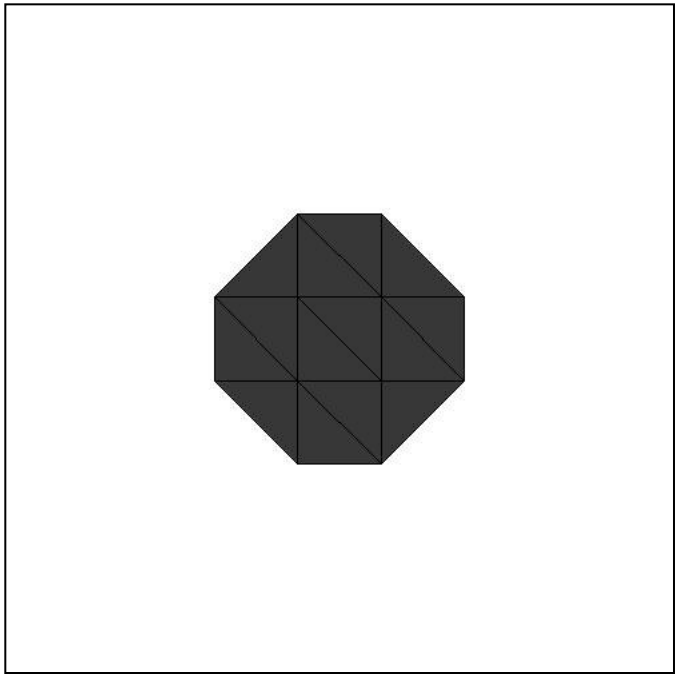


decomposition of mesh



- Liquid and gas regions are determined using probability.

Test problem (isothermal expansion)



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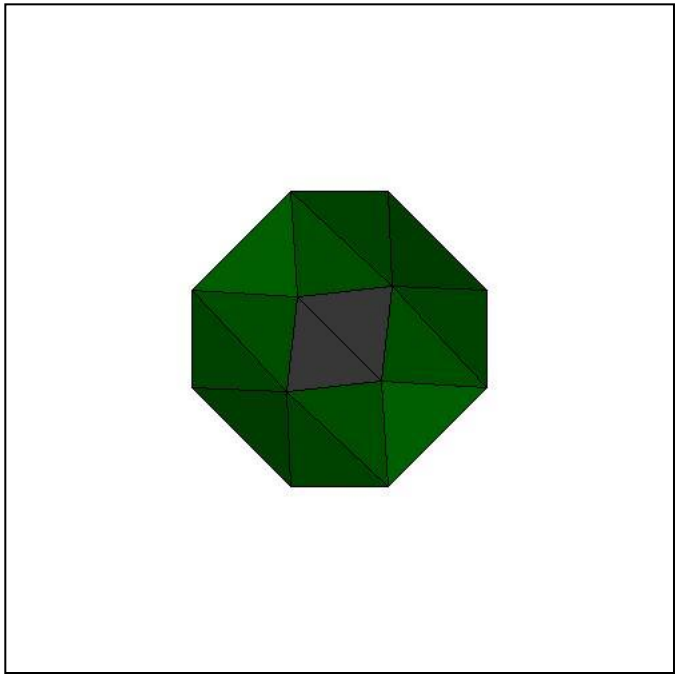

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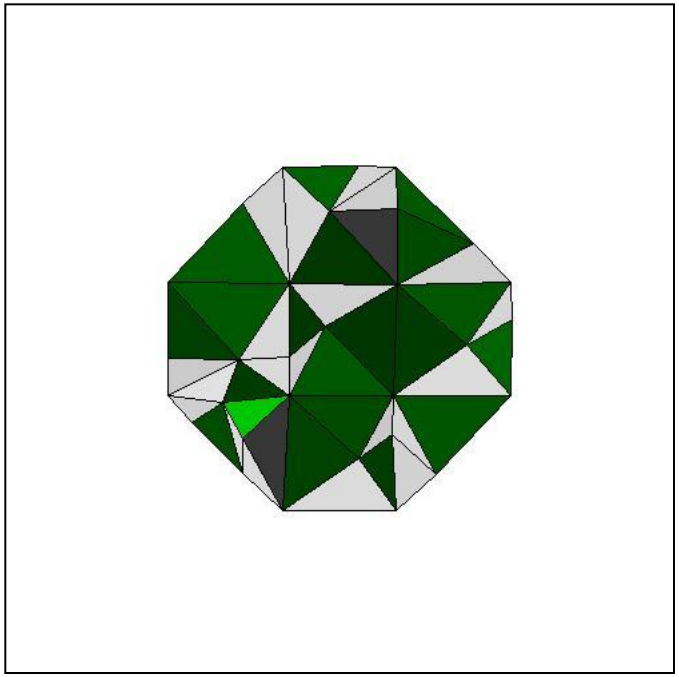

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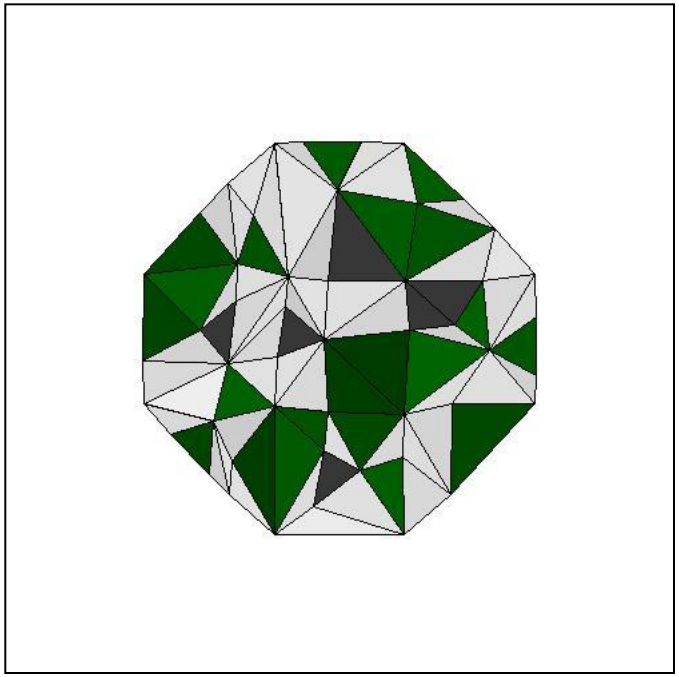

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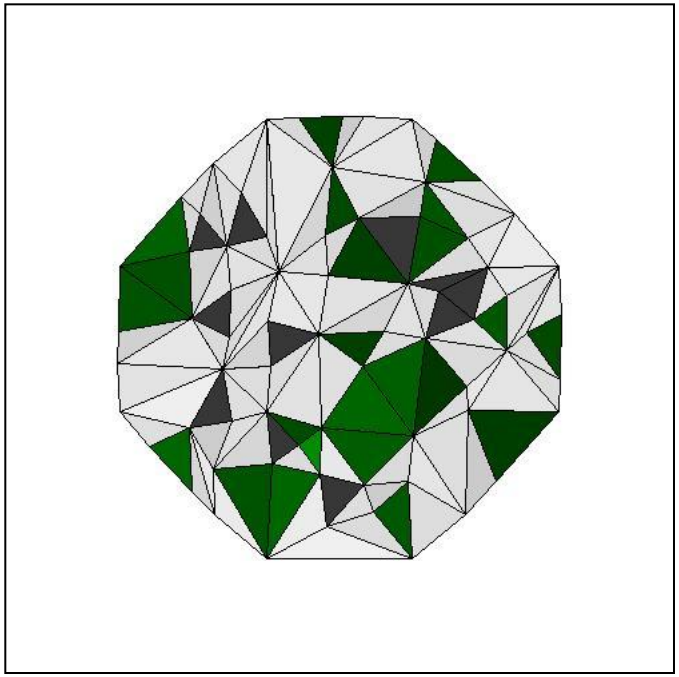

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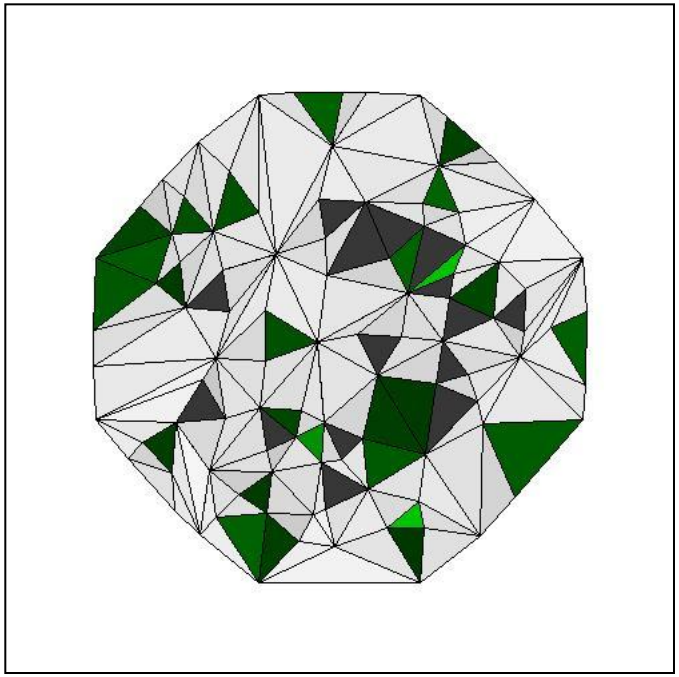

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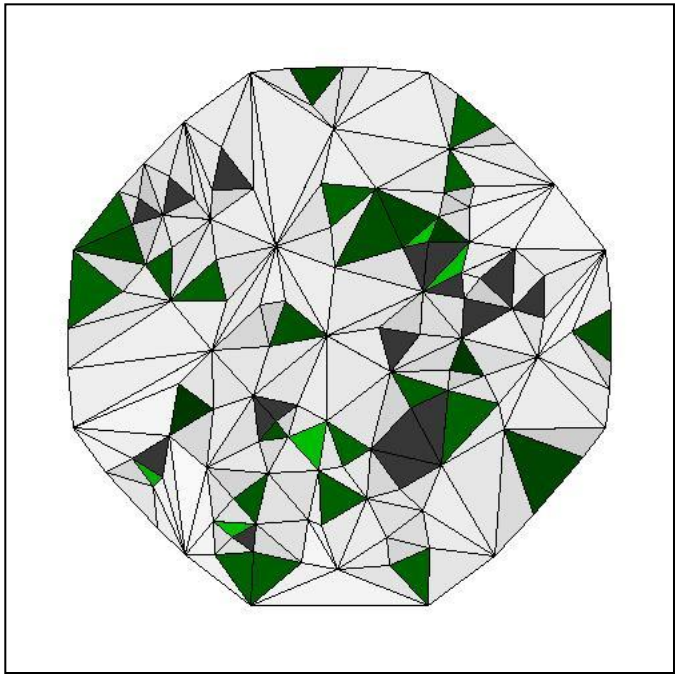

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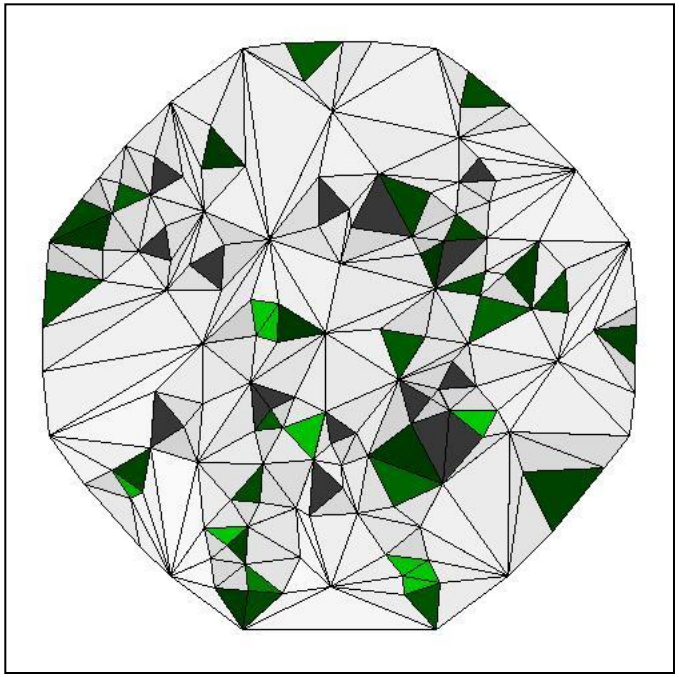

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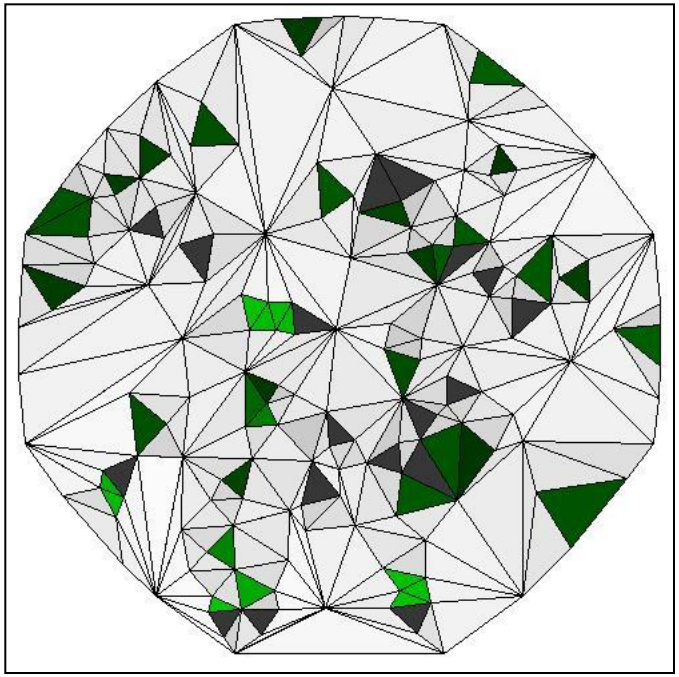

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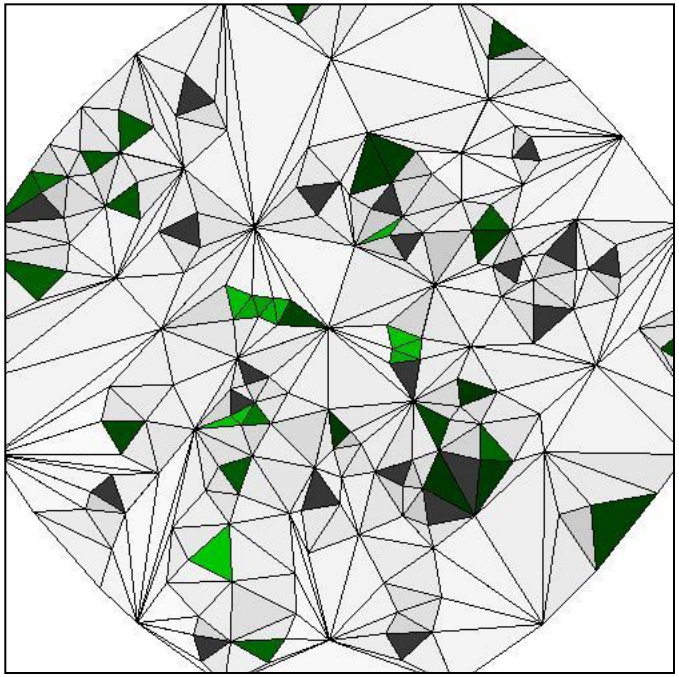

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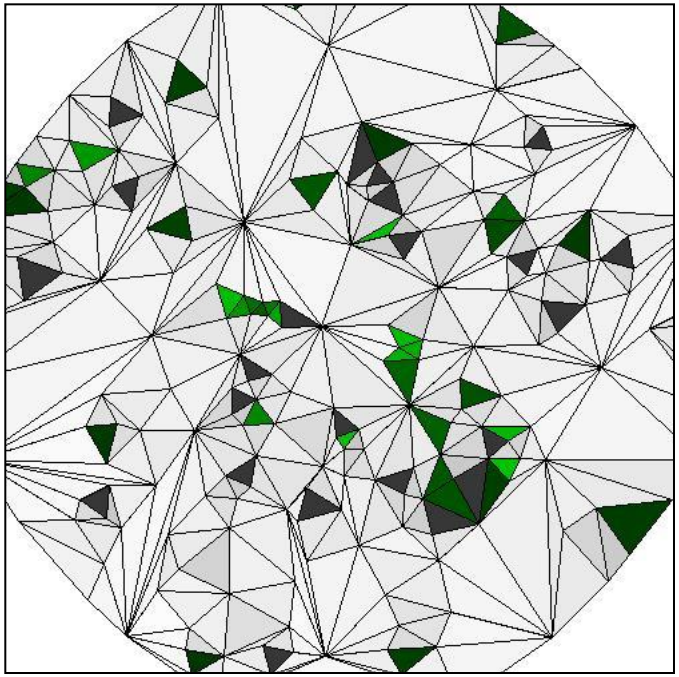

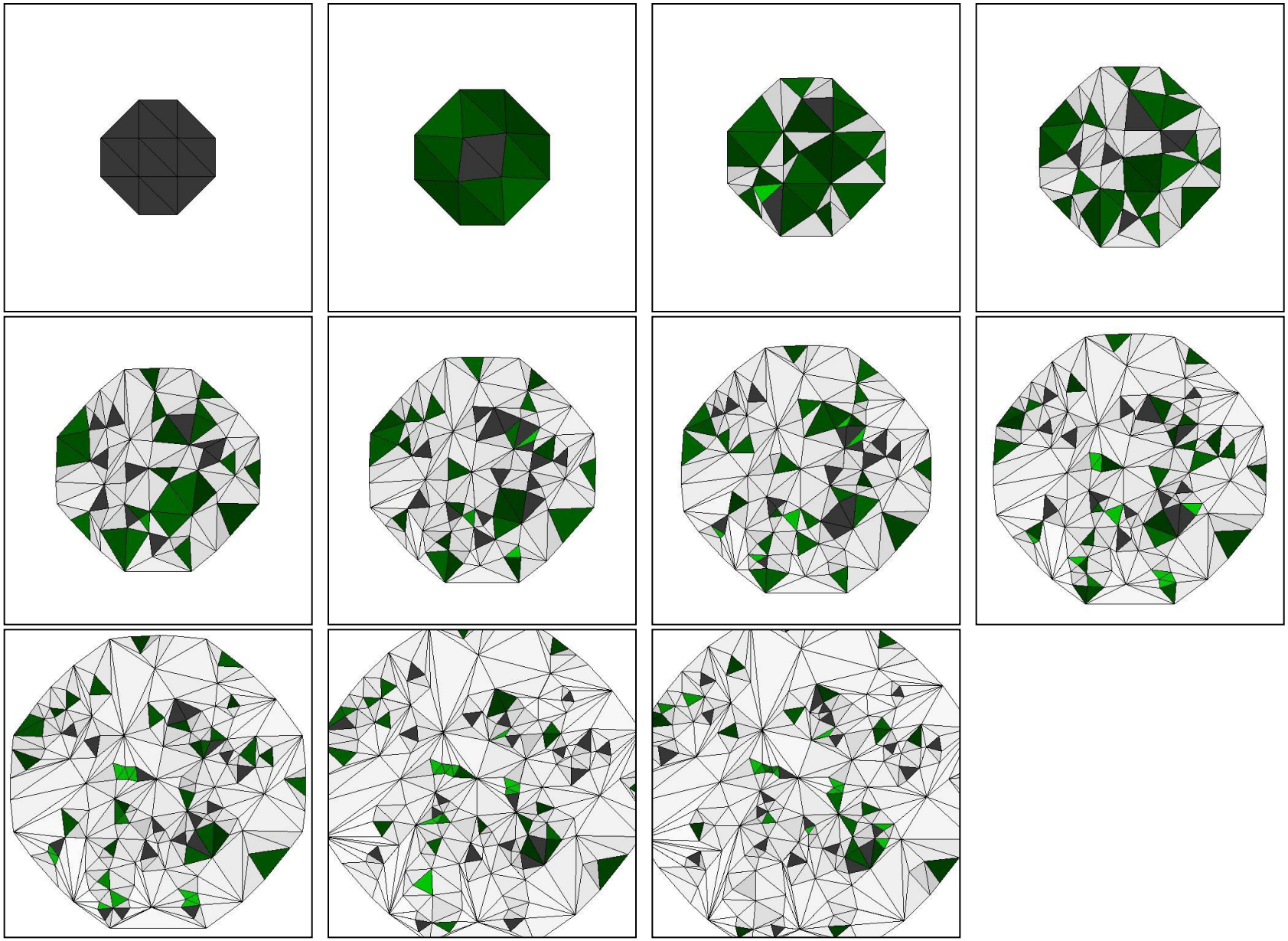

Summary

- For the development of short wavelength source and efficient 13.5nm source, models of atomic processes and hydrodynamics are investigated.
- New hydrodynamics model, which takes instabilities in the initial plasma formation into account and capable of reproducing mist formation, are being tested.
- Development of reduced atomic processes and radiation hydrodynamics model is being considered as a new research project.